Chapter 9. Cost Analysis of the Stage-1 VLHC

9.1 Uses and Limitations of the Cost Analysis for This Study

Within the scope of this design report, the development of a preliminary cost estimate of the major cost elements is useful and reasonable. A cost estimate at this early stage of the design and development is inherently limited, but can nevertheless give a “ballpark” figure for the total cost of the collider. Furthermore, reasonable crosschecks with known costs and historical data for similar systems can serve to give one confidence in the result. Hence, the costs associated with individual systems can and should be accurate even at this early stage. The major weaknesses of making estimates without complete and proven designs, and without extensive fabrication experience, is the high probability of leaving out many of the minor subsystems and necessary infrastructure and activities that go to make the whole out of the sum of the parts. Even in that case, comparisons with complete accelerators and cost estimates of mature designs, viewed from a high level, can be used to verify costs, and, in particular, to set upper bounds, provided that the historical data are accurate. The results can then be used, along with physics analyses and technical evaluations, as input into the important matter of deciding which facilities the high-energy physics community should build. Finally, and perhaps most importantly, analysis of the major cost drivers is useful as a means to identify systems where further R&D and engineering can net substantial reductions in cost.

9.2 Identification of the Cost Drivers

The nine major cost drivers, listed in Table 9.1, were chosen as a result of the past experience of the participants in the design study. Most of them are obvious, such as the underground construction, surface construction, and the main magnet systems and associated cryogenics. The unusually long magnets and large tunnel circumference led us to believe that there might be important issues to discover in the installation activity, such as the need for sophisticated tooling or very long travel times. The vacuum system is conventional and room temperature, but its extensive size requires many components, and hence, the possibility of high cost. The interaction regions were chosen because they are likely to be complex—and therefore interesting—and considerably more costly than the total cost of their components.

Once the high-level cost drivers were identified, engineers and scientists used the technical descriptions to make cost estimates. If possible, we obtained quotes from industry as aids in the estimates. This was particularly true for very large subsystems, such as steel and superconductor for the magnets, and the refrigerators for the cryogenic system. In many cases, recent purchases and contracts were used as guides to the costs of components, such as the cost of assembling steel laminations into yoke subassemblies, which was estimated from the known cost of the same activity for the Fermilab Main Injector. Labor, overhead and profit was, of course, included in the cost of delivered subsystems estimated by industry. Other labor, e.g., for the final assembly, test and installation of the magnets was estimated by engineers using models created by them for the activity being estimated. Standard Fermilab labor rates were used in those cases, including complete fringe benefits but not overhead or other indirect costs.

Table 9.1. The major cost drivers and the associated technical description section.

Cost Driver	Report Section
Main Magnets	5.1.1, 5.1.6, 5.1.7
Corrector Magnets & Special Magnets (Injection, etc.)	5.1.3, 5.1.5
Interaction Regions	5.1.4
Refrigerators	5.2.1
Cryogenic Systems	5.2.1
Vacuum System	5.2.4
Installation	5.1.8
Civil Construction – Above Ground	7.5, 7.6
Civil Construction – Below Ground	7.2 – 7.5

The cost drivers were developed by estimating the cost to build the current design, as presently known, in FY2001 dollars, at FY2001 prices. There is no assumption of future piece cost savings due to the successful completion of current or future R&D programs, or manufacturing scale-up possibilities. This estimate assumes that a complete design exists, and all major R&D programs necessary to prove and complete the design have been finished before the start of construction. The estimate is for production and installation only. In places where the bottoms up estimates as developed do not appear consistent with experience, modifications were made to bring them more in line with past experience. Only the direct costs for the major cost drivers are estimated. Engineering, design, inspection and administration (EDI&A) and indirect costs such as G&A are not included, but are estimated in the analysis section as a complement of professional and support personnel over the duration of the project. Finally, the estimates do not include commissioning, pre-operations, R&D, detectors or land acquisition; nor does it include escalation and contingency.

These rules make this cost analysis consistent with a so-called “European” or raw cost model, which excludes all of the factors we have excluded, including EDI&A and contingency. This is an appropriate way to get at an estimate useful for a comparisons of costs of different facilities, since almost all of the adjustments necessary to get a “U.S.” cost estimate are multiplicative and apply to all raw estimates equally. The one exception is the assignment of appropriate contingency. Contingency is specific to each project and depends on a risk analysis that takes into account the state of the design, engineering, prototype fabrication and certain economic factors at the time the risk analysis is done.

9.3 Models for Estimating the Cost Drivers

The cost estimate for the largest cost element, the underground construction, was done by a collaboration of CNA Consulting Engineers, Minneapolis, MN, and Hatch-Mott-McDonald, Toronto, Canada, under contract to Fermilab. They estimated three ring orientations, as described in Chapter 7, not because those are the preferred sites—there are no preferred sites as yet—but in order to get a range of costs due to different physical and geological features in the Fermilab area. The result is not only an estimate that defines a range of costs for the underground construction, but also a set of building blocks that can be used to estimate the cost of underground construction with different ring orientations, different ring designs and different included features. The cost number for underground construction in Table 9.2 is the approximate average of the costs for the three ring orientations, which did not differ from each other by more than $100 million. The underground construction includes all necessary shafts and ramps, and the underground adits and two large collision halls, in addition to conventional outfitting costs such as HVAC, AC power distribution, groundwater pumping, staircases, elevators and so forth. The underground construction also includes the cost of an AE/CM firm, based on 17.5 percent of the underground construction cost. This firm manages the underground construction. The Laboratory EDI&A needed to oversee the AE/CM firm is not included. The surface buildings, including the six cryogenic service buildings and the surface features above the collision halls were estimated based on footprint area by Fermilab's Facilities Engineering Section, using standard rates similar to those used for recent accelerator estimates. Those estimates include utility installation, such as power and water.

The main magnet estimate includes costs for fabrication and procurement of all main and dispersion suppressor dipoles in the Stage 1 ring, including both the magnet and the directly associated cryogenic piping and return conductor. The model used is similar to the one used to build the Main Injector at Fermilab. Large subassemblies appropriate for shipping over roads, such as 11-m yoke sections or beam tubes, are built in industry and delivered to a final assembly building near an installation ramp at the VLHC site. The final assembly and testing is done at that factory site and either stored temporarily or immediately installed in the tunnel. Costs for the correctors and straight section magnets are separately included. We assume that most of them will be built in industry. The interaction-region magnets are also separately estimated. Since they are technically challenging, they will probably be built either at Fermilab or another laboratory with extensive superconducting magnet experience.

The estimate for the cryogenic system was split into two pieces—the refrigerator package and the pipes and valves in the tunnel not included in the magnet system. This was done because the refrigerator package can be estimated by industry and fits a well-known cost curve as a function of power, while the delivery system is very design specific. The refrigerator package includes the fabrication, installation, and commissioning of the six refrigerators required for the ring, and the additional refrigerators required for the interaction regions. The tunnel cryogenic system estimate includes the fabrication, installation and checkout of components necessary to deliver cryogenics from the refrigerators up to and including the distribution box at the end of each magnet string.

Frequently, we had to make somewhat arbitrary decisions as to which system a particular component fell. For example, all the pipes for the cryogenic system that are in the magnet are included in the magnet system. The vacuum system estimate includes all vacuum components, including the beam tube extrusion. Hence, the magnet system does not include the beam tube as part of its cost. The installation estimate covers magnet installation, including magnet stands, alignment, and special tooling for handling the 65-m magnets; and the installation of tunnel infrastructure, such as lighting, trolley rails, cable trays and pipe hangers. In order to get a total cost estimate, we had to include an estimate for the total of the "non-drivers," that is, the minor subsystems. We did this by taking the ratio of those minor accelerator systems—power supplies, RF, instrumentation, controls, safety systems, beam abort line and dump, and accelerator utilities—that were part of the SSC 1990 Site Specific Cost Estimate [1] to the accelerator systems we did estimate. Those minor systems amounted to less than 10 percent of the SSC Collider cost.

9.4 Results and Analysis

Table 9.2 lists the results of the cost driver exercise. The most important thing to notice is that more than half the total cost is in the civil construction, and almost all of that is in the underground part. Traditionally, 40 percent or more of underground construction is in labor costs. R&D to reduce the number of workers by using straightforward automation techniques common in other industries and even in the construction industry could significantly reduce costs, while at the same time improving safety because fewer workers will be underground. Also, the details show that half the underground cost is in features other than the arcs, such as the necessary collision halls, adits and breakouts added to the tunnel. This indicates that discipline and coordination between accelerator designers and tunnel builders to eliminate unnecessary special features could significantly reduce costs.

Table 9.2. The estimated costs of the major cost drivers for Stage-1 VLHC.

Stage-1 VLHC Cost Driver	Cost Estimate (in FY2001 M$)	Fraction of Total Stage-1 Cost
Total Cost	**4,138**	**100 %**
Construction – Below Ground*	**2,125**	**51.4 %**
Construction – Above Ground	**310**	**7.5 %**
Main Arc Magnets	**792**	**19.1 %**
Correctors & Special Magnets	**112**	**2.7 %**
Refrigerators	**95**	**2.3 %**
Other Cryogenic Systems	**22**	**0.5 %**
Installation	**232**	**5.6 %**
Vacuum System	**154**	**3.7 %**
Interaction Regions	**26**	**0.6 %**
Other Accelerator Systems	**270**	**6.5 %**

* *The below-ground construction cost is the approximate average for the total underground construction in the three different ring orientations, based on 12 ft. diameter tunnels. The maximum cost difference is less than $100 million. The cost includes 17.5 percent for an AE/CM firm.*

The second cost driver is the main arc magnet system. The cost of these magnets is about $900 per Tesla-meter, much less than the present-day cost of a cos-theta NbTi dipole, which is around $2500/T·m. The cost of the transmission-line magnet is dominated by steel laminations, not by superconductor as in other styles. Research into the use of commodity steel for these magnets, or improvements in stamping and stacking that small-scale magnet builders have not used in the past are likely places to look for cost reductions.

Continuing the work on the engineering study will sharpen the cost estimate and further focus the R&D on the most important parts of the VLHC. This is extremely important.

Additionally, increasing the R&D to a point where industry can reasonably be involved will also sharpen the cost estimate and reduce the needed contingency. Both of these efforts must continue at a more vigorous pace.

9.5 The Reality Checks

The relatively low cost of the Stage 1 VLHC is a bit surprising when compared to that presented recently by the TESLA Collaboration for a superconducting linear collider at much lower energy. This is largely so because magnets are much less costly than RF cavities and RF power systems, and tunnels are less costly than magnets. It pays to make some comparisons with other machines or cost estimates. We have attempted to put our cost analysis side-by-side with the baseline cost estimate of the collider ring of the SSC. That cost estimate was mature by 1991, and in spite of many rumors to the contrary did not significantly change between 1991 and the end of the project.

In order to make the comparison, we used the estimates in reference [1], adjusted to contain only the collider-ring costs, and to include the fractions of the accelerator-wide costs that apply to the collider ring [2]. The results were then deconstructed and reconstructed into categories that are parallel to the VLHC system categories. For example, corrector magnets in the SSC baseline cost estimate were not part of the magnet system, but were included in the accelerator system estimate. One can only imagine why. After the reconstruction, the SSC baseline was inflated from 1990 to 2001 dollars by the consumer price index (CPI), a 35 percent increase. The actual inflation may be somewhat less. The producer price index between 1990 and 1998, the last year with complete data, show significantly lower inflation, more like 15 percent. Since large projects like the SSC and the VLHC would procure much of its material directly from manufacturers, that lower rate would apply in some cases. The system-by-system cost comparisons are shown by percent of the total cost in Table 9.3. The SSC total cost inflated to 2001 dollars is $3.79 Billion, very close to the same as the VLHC at the same center-of-mass energy, even though the distribution of costs in civil construction and magnets is almost exactly reversed.

Table 9.3. A comparison by major system of the Stage-1 VLHC costs and the SSC baseline cost escalated to FY2001 dollars.

Collider System	Fraction of total Stage-1 VLHC Cost	Fraction of Total SSC Collider Ring Cost
Total Cost	**100 %**	**100 %**
Construction – Below Ground	**51 %**	**15 %**
Construction – Above Ground	**8 %**	**5 %**
All Magnets (except IR)	**22 %**	**61 %**
All Other Collider Systems	**19 %**	**19 %**
Total Cost in FY2001 M$	**$4,138**	**$3,790**

The appearance that the inflation-adjusted SSC cost and the Stage-1 VLHC cost is a bit artificial because of the uncertainty in the cost estimates and in the cumulative inflation rate. Nevertheless, there is no denying that they are close. Some conclusions can be drawn from this. First, it implies that the Stage-1 VLHC cost is not wildly wrong. Second, it says that less costly low-field magnets and simple magnet-related systems compensate for the higher cost of the big tunnel required for the Stage-1 VLHC. This is very good news, because the large-circumference tunnel will be a major cost driver for the 200 TeV Stage-2 VLHC. As we hoped when the concept of a staged VLHC was born, paying for the large-circumference tunnel during Stage-1 is not a significant cost penalty, and it will save over $2 Billion during construction of the 200 TeV collider.

References

[1] *Report on the Superconducting Super Collider Cost and Schedule Baseline*, DOE/ER-0468P, January, 1991.

[2] Dr. John Marriner performed this exercise and kindly shared his spreadsheets with the VLHC Study.